

DETAILED WORK PLAN

Experimental Overview

It is expected that this study will be conducted in two phases. Phase I will entail a review of existing literature including various state practices where the required weight of cementitious materials required for use in pavement concrete has been reduced, the finalization of the Phase II experimental plan, and the acquisition of materials needed for the next phase. In Phase II, a laboratory experiment will be conducted in which representative pavement concrete is made with standard and reduced cementitious materials and tested to assess engineering properties and long-term durability. This data will be analyzed and a final report prepared that recommends 1) justifiable revised minimum cementitious material contents that can be used by WisDOT in the future, and 2) future work that can be used to further improve the results of this study. This project will be done in two phases, each consisting of three (3) tasks, which will be completed over 24 months.

Experimental Plan

Phase I

Task 1 – Review of Existing Literature. This task will examine the current body of knowledge with respect to concrete paving mixtures using cementitious contents (cement plus SCM) less than WisDOT's current 565 lbs/yd³, with particular emphasis place on constructability, engineering properties including strength and permeability, and on long-term durability. In addition to the vast amount of information already amassed at Michigan Tech on this and related topics, other sources of relevant information will be sought from the following sources:

- The Transportation Research Information Services database (TRIS).
- Compendex database.
- Internet Databases (e.g. ALTAVISTA, Google).
- Various SHRP and RILEM publications.
- Topic searches on the Community of Science and Science citation web pages will be conducted and individuals and groups that have been involved with fly ash specifications and testing will be identified (in addition to the large numbers of those already known by the investigators).
- Midwest DOT specifications.

Task 2 –Revision to the Phase II Experimental Plan. Based on the results of Task 1, the Phase II experimental plan as presented in this proposal will be reviewed and revised as necessary. This revised experimental plan will be submitted for review by WisDOT.

Task 3 – Material Acquisition. To keep the project on schedule, concrete making materials will need to be obtained and stored for use in the course of this study. Michigan Tech maintains a palletized material storage facility that will allow stockpiling of all needed materials so that single shipments of cement, SCMs, admixtures, and aggregate can be used for all experimental work, eliminating batch to batch variations. The following materials will be used in this project:

- Portland cement: Three (3) sources of portland cement will be used. They will be Lafarge Alpena Type I/II ($\text{Na}_2\text{O}_{\text{eq}}$ 0.43%) , Holcim Clarksville Type I ($\text{Na}_2\text{O}_{\text{eq}}$ 0.67%) , and St. Mary's Charlevoix Type I ($\text{Na}_2\text{O}_{\text{eq}}$ 0.86%). The properties for these cements, based on recent mill certifications, are presented in Table 1.
- Ground granulated blast furnace slag (GGBFS): One (1) source of GGBFS will be used in this study. The GGBFS will be obtained from either Holcim or Lafarge.
- Fly ash: Two (2) sources of Class C fly ash (both Lafarge sources: Columbia Plant at Portage and Weston Plant at Wausau). The properties for the fly ash, based on recent mill certifications, are presented in Table 2.
- Air entraining admixture (AEA): One (1) source of AEA will be included. It will be vinsol resin-based, most likely BASF MB VR Standard, as Michigan Tech has worked with this admixture on a past WisDOT project.
- Water reducer (WR): One (1) source of low-range water reducer will be used in this study. A BASF Polyheed 1020 Type D WR will likely be used. The same manufacturer must be used for all chemical admixtures.
- Coarse aggregate: Two (2) sources of coarse aggregate will be used. One will be a igneous glacial gravel from northern WI with a fine aggregate from the same source. The second a crushed dolomite from southern WI with a fine aggregate typical of those found in southern WI.

Table 1. Properties of portland cement proposed for use in the study.

Cement ID	PC-1	PC-2	PC-3
Chemical Composition (%)			
SiO ₂	20.1	19.5	18.9
Al ₂ O ₃	4.7	4.8	5.4
Fe ₂ O ₃	2.7	2.6	3.1
CaO	63.9	63.8	62.6
MgO	2.4	3.9	3.1
SO ₃	2.6	3.0	3.8
LOI	1.37	1.4	1.9
Insoluble residue	0.32	0.23	0.14
Free Lime	1.62		
Limestone		2.3	3.19
CaCO ₃ in limestone		96	80
C ₃ S	64	62	60
C ₂ S		9	9
C ₃ A	8	8	9
C ₄ AF		8	9
Total Alkalis (NaO _{eq})	0.43	0.67	0.86
Physical Test Results			
Blaine Fineness (m ² /kg)	367	377	381
Passing #325 sieve (%)	95.4	89.5	94.1
Compressive strength (C 109)			
1 day (psi)	1980		2681
3 days (psi)	3670	4110	3920
7 days (psi)	4640	4950	4590
28 days (psi)	5760	5970	5557
Vicat setting time			
Initial (min)	100	96	70
Final (min)	210	242	
Air content (%)	6.3	7.0	8.0
Autoclave expansion (%)	0.11	0.12	0.11

Source:

PC-1: Lafarge Alpena, MI Type I

PC-2: Holcim Clarksville, MO Type I

PC-3: St. Mary's Charlevoix, MI Type I

Table 2. Proposed properties for fly ash sources to be used in the study.

Fly Ash ID	FA-1	FA-2
Chemical Composition (%)		
SiO ₂	33.49	38.49
Al ₂ O ₃	18.08	18.85
Fe ₂ O ₃	4.95	6.45
Total SiO ₂ , Al ₂ O ₃ , Fe ₂ O ₃	56.5	63.8
CaO	24.87	20.36
SO ₃	2.34	1.11
MgO	5.73	4.79
Na ₂ O	1.86	1.58
K ₂ O	0.36	0.70
Na ₂ Oeq ¹	2.10	2.04
LOI	0.26	0.33
Physical Test Results		
Retained on #325 sieve (%)	15.4	16.7
Strength Activity Index		
Ratio to control @ 7 days	108	93
Water Req., % of control	94	94
Soundness, autoclave expansion (%)	0.13	0.07
Density	2.74	2.63
AASHTO M 295 Classification	C	C

$$^1 \text{Na}_2\text{O} + 0.658 \text{K}_2\text{O}$$

Source:

FA-1: Lafarge Columbia Plant at Portage

FA-2: Lafarge Weston Plant at Wausau

Phase II

Task 4 – Execute Phase II Experimental Plan. The laboratory investigation presented here reflects the current thinking of the project team. The Phase II experiment by nature will be limited in scope and a statistically based experimental design is being proposed to maximize the usefulness of the results for the given level of support. Using the materials presented in Task 2, the following concrete mixture parameters are being considered for use in the experiment:

- Cementitious materials content: Will vary from 565, 517, 470, 423, and 376 lbs/yd³. As will be described, emphasis will be placed on 565, 470, and 376 lbs/yd³ to define the non-linear trends within the range of inference with supplemental work using 517 and 423 lbs/yd³ for confirmation.
- Cementitious material combinations: Ordinary portland cement and binary systems consisting of 30% fly ash or 50% GGBFS will be considered
- One fresh air content: $6 \pm 1\%$
- Aggregate size and proportion: The aggregate must consist of coarse (predominant 1 in to 3/4 in retained), intermediate (predominant 3/8 in to No. 4 retained) and fine (No. 8 and finer) fractions graded in accordance with what is commonly known as the Shilstone Method. Previous research indicates that this project will not be successful if conventional gap grading of aggregates is to be used. Further, the maximum aggregate size is often larger than what is currently used, with some successful mixtures using 1-1/2 inch maximum aggregate size. As a result, it will not be possible to use an AASHTO #67 grade coarse aggregate and hold the fine aggregate volume constant at 40% of total aggregate weight. An aggregate proportion that meets the Shilstone requirements will be selected and held constant for all mixtures and the aggregate volume will be altered to accommodate the changing volume of the cementitious materials.
- Water content and *w/cm*: The *w/cm* must be held constant (it is suggested that a *w/cm* of 0.45 be used) as this is the single most important parameter affecting the behavior of hardened concrete (e.g. strength, permeability, shrinkage, etc.) as it directly impacts the capillary pore system. Therefore the water content will be adjusted as the cementitious content varies. To maintain an acceptable slump of 3 ± 1 , the amount of water reducer will be varied.

The number of materials and mixture parameters that are being considered results in a 120 mixture combinations if all are tested. Using the ANOVA table and F tests to analyze the results will require at least two (2) replicates, thus over 240 batches would need to be produced and tested. Obviously, this is impossible given the resources available for this project.

To reduce the number of mixtures required to a reasonable number, two models will be built using two separate experiments. The first experiment will be based on the three (3) cements without the use of SCMs and only the two (2) extreme and the middle cementitious materials contents (565, 470, and 376 lbs/yd³). This will reduce the experiment to a 3 x 2 x 3 full factorial design (three (3) cement types, no SCMs, two (2) aggregate types, and three (3) cementitious materials contents). Two (2) replicates will be made for each of the 18 mixture designs, resulting in a total of 36 batches being made and tested. Statistical models will be built to quantify the effect of each mixture variable (i.e. material or mixture parameter) for each of the test (e.g. strength, F-T durability, permeability) and statistical tests will be performed to identify important variables, variable levels and possible interactions among the variables. In addition, four (4) mixtures will be evaluated (a total of eight (8) batches once replicated) using a cementitious materials content of 517 and 423 lbs/yd³ to verify the validity of the developed models. In total, 44 batches of concrete will be made and tested in this first experiment.

The second experiment will be guided by the results of the first. It is anticipated that a 3^{3-1} fractional factorial design (FFD) will be run with two (2) replicates. The three (3) variables will be cement type, SCMs, and cementitious materials content (565, 470, and 376 lbs/yd³). Each has three levels. A single coarse aggregate source will be selected for this part of the experiment based on the results of the first experiment. A full factorial design would require a total of 54 mixtures that when replicated would require 108 batches of concrete. The proposed FFD would require only 18 mixtures or 36 additional batches of concrete to be made and tested. But this is a resolution III design, meaning that the ability to separate main factor effects from interactions among the factors will not exist. However, it is anticipated that the main effects will be much larger compared to the interactions, which justifies the use of this design. If the data collected from this experiment shows strong interactions, additional mixtures can be created and tested to regain the ability to separate the main effect from interactions. Similar statistical analysis mentioned earlier will be carried out on the results. Table 3 presents the proposed experimental matrix for the fractional factorial design. An XX in a cell of the table indicates that two replicates will be run on the mixture described by that cell.

Table 3. Experimental design for fractional factorial design for Experiment 2.

SCM	Lafarge Alpena			Holcim Clarksville			St. Mary's Charlevoix		
	565	470	376	565	470	376	565	470	376
Fly Ash 1	XX					XX		XX	
Fly Ash 2		XX		XX					XX
GGBFS			XX		XX		XX		

The testing that will be conducted will be used to assess a number of fresh and hardened concrete properties. Testing of fresh and hardened concrete, conducted in Michigan Tech's CCRL inspected facilities, will include:

- Total air content (AASHTO T152): 1/batch
- Slump (AASHTO T119): 1/batch
- Unit weight and yield (AASHTO T121): 1/batch
- Compressive strength (AASHTO T22): 8/batch testing 2 each at 3, 7, 28, and 90 days
- Splitting tensile strength (AASHTO T198): 8/batch testing 2 each at 3, 7, 28, and 90 days
- Freeze/thaw durability (AASHTO T161 Method A): 3/batch tested to 300 cycles after 28 day moist cure and 28 days air cure.
- Shrinkage (ASTM C157): 3/batch tested at 28 days
- Sorptivity (ASTM C 1585): 2/batch after 7 days moist cure and 49 days air cure
- Rapid chloride permeability (AASHTO T277): 3/batch sawed from single cylinder moist cure and test at 90 days

Task 5 – Data Analysis. The data collected in Task 4 will be thoroughly analyzed to establish trends and determine gaps that remain in the knowledge regarding minimizing cementitious materials content in paving concrete. Based on this analysis, recommendations will be made for revision to WisDOT's minimum cementitious materials specifications and for further work to help clarify any unresolved issues.

Task 6 – Final Report. A final report will be prepared that describes the results of both phases of the study. Recommendations will be made with regards to implementing the results as justified by the results and for future work as needed to fill in any remaining knowledge gaps. This report will be presented to WisDOT at the conclusion of the study.

WORK TIME SCHEDULE

Task	Year 1												Year 2											
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
Review of Existing Literature																								
Revision to the Phase II Experimental Plan																								
Material Acquisition																								
Execute Phase II Experimental Plan																								
Data Analysis																								
Final Report																								

REPORTS

Progress reports will be provided on a quarterly basis. The final report will be provided as Task 6 of the project. The research team will communicate with the Wisconsin Highway Research Program regarding variations or revisions in the work plan as they occur.